THE GEOLOGY OF LA SAL MOUNTAINS OF UTAH

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LAURENCE M. GOULD

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I. Physiography

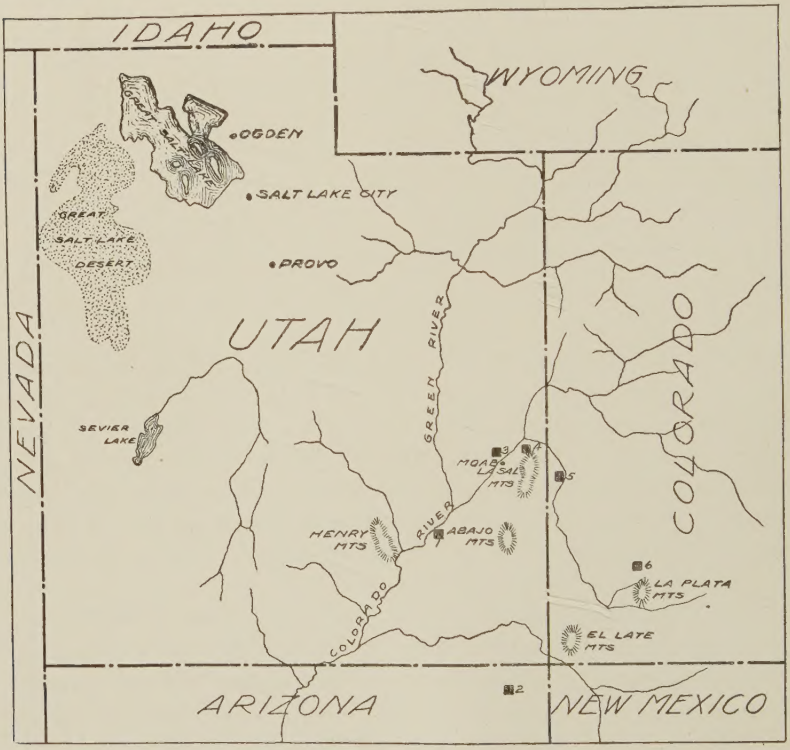
LA SAL MOUNTAINS lie within the great Colorado plateau country so notable for its cliffs and canyon walls which exhibit with unparalleled perfection great cross-sections of the earth's history. The mountain group is nearly bisected by the meridian of 109 degrees and 15 minutes west longitude and lies between 38 degrees and 20 minutes and 38 degrees and 35 minutes north latitude (Map 1). The Colorado–Utah boundary line is distant only seven miles to the east.

One's first impression of this plateau country is deceptive. It seems to be a relatively flat surface possessing no marked features of relief; one needs to travel but a short distance across it, however, to be undeceived. It is found to be dissected by a veritable maze of canyons, most of which are steep-walled and present few favorable crossings. Permanent streams are found in only a few of them. The deceptive character of the topography is due primarily to the fact that there are practically no features, aside from the mountains themselves, which have been caused by uplifts of any consequence. The immense incisive work of running water over a once relatively flat surface

has been the major factor in the development of this peculiarly deceptive relief. The almost total absence of depositional features further accentuates the results of the stream action.

Influence of Structure on the Erosional Processes

In the erosional processes which have been operative, whether due to wind or water, the rock structures have con-



MAP 1. Index map to show location of La Sal Mountains and other laccolithic mountains of neighboring regions and of the areas from which the columnar sections of Figure 1 are copied or derived

trolled to a marked degree. Indeed one might almost say that the present physiographic development is a direct reflection of the structural features of the plateau province. Longitudinal

fractures along the nearly flat-lying anticlines facilitated the establishment of streams until these structures have become valleys separated by mesa-like lands which represent the synclinal areas. Joints and faults in the Navajo sandstone, which covers so much of the surface west of the mountains, have controlled the weathering and erosional processes with the production of rounded and elongated dome-like forms almost equally spaced. Northwest of the mountains, where the Wingate is the cover rock, fractures and joints have caused the formation of great mesas, which with the passage of time have been subdivided into smaller mesas and these in some places into buttes often capped only by small pinnacles (Pl. I, Fig. 1) of what formerly was an extensive overlying rock.

Work of Running Water and Wind

Because of the immense amount of denudation which this region has undergone since Tertiary time, it is not possible to estimate the rate of the various agents operative in this semi-arid climate, or to evaluate with any degree of accuracy their relative importance. It is obvious, however, that running water has played the major rôle. The sparseness of the vegetation has been an important factor in the operation of this process as well as in the work of the wind. The run-off is extremely rapid and correspondingly effective in its erosional effects. In but a few minutes what seems to be a small rain may fill perfectly dry washes with raging torrents which transport enormous amounts of detrital matter. In an almost equally brief time enough water and débris may be added to the Colorado itself from side canyons to change it from a rather shallow stream, sluggish in places with noticeable sand bars, into a muddy turbulent river carrying an immense load. In the various weathering and erosional processes which are contributory factors to the efficiency of this sort of denudation, wind, temperature changes and frost, in the order named, are the most important. The wind is effective in two ways. In the first place it is an important agent of transportation in bringing much sand and other detritus to the streams or canyons where it may be further worked over and carried away.

Again, in the formation of many of the land forms which now stand out in relief, wind action is seen to have been a dominant factor. Mention has already been made of the buttes and mesas in the Castle Valley region, which show in part the effects of wind, but a much more interesting group of such erosion remnants are the so-called "windows." These lie on the west side of Colorado River about twelve miles northwest of Moab. Here is a veritable museum illustrating the varied and fantastic forms that may result from wind-weathering and erosion. Joints together with cross-bedding have so controlled the denudational processes that massive castellated forms, chimneys, caves, bridges and arches of great variety have been developed (Pl. I, Fig. 2). This group of features presents such unusual scenic effects that from this standpoint alone they are deserving of wider recognition, and it is of interest to note that a movement is now on foot to have this unique region set aside as a national monument.

As one proceeds towards the mountains from the west, he is impressed with the changing profiles presented by the various physiographic forms. Whether the route is through Castle Valley (Pl. I, Fig. 1) or makes its way up over the sand flats (Pl. II, Fig. 2) from Moab, the sharp clean-cut erosion forms of semi-arid climates dominate the early part of the trip. As one ascends the first mesas west of the mountains, these give way to softened slopes and to land surfaces partly covered with vegetation, and finally as one climbs the last shelf adjacent to the foot of the mountains he finds himself on rounded forms such as characterize humid climates.

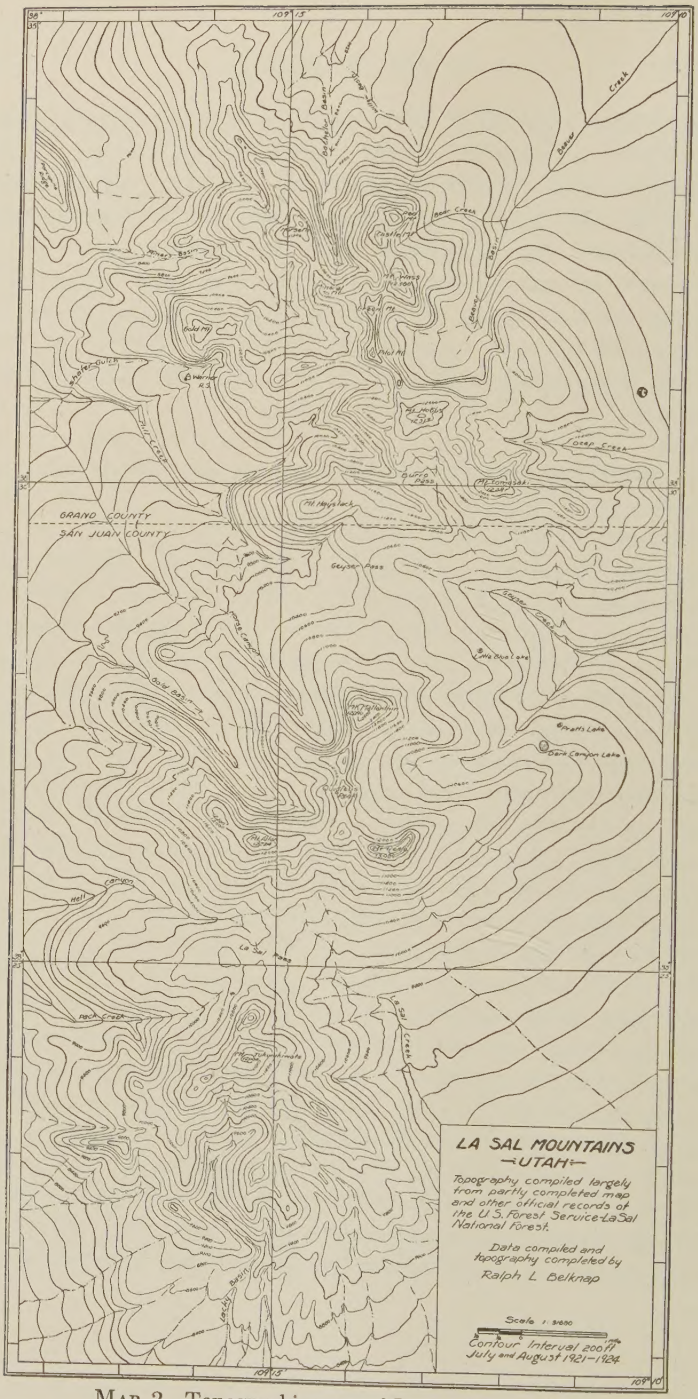
Vegetation is much thicker and the lower slopes of the mountains are densely forested with aspen and spruce. As one finally stands on the mountain tops the contrasted aspect presented by the plateau country on the Colorado side of the mountains as compared with that on the Utah or western side is very striking. To the west, except for the forested slopes of the mountains themselves and the vegetation-covered mesas that stretch a few miles out into the plateau lands, the landscape is largely one of bare rock surfaces. Even from so great a distance all manner of

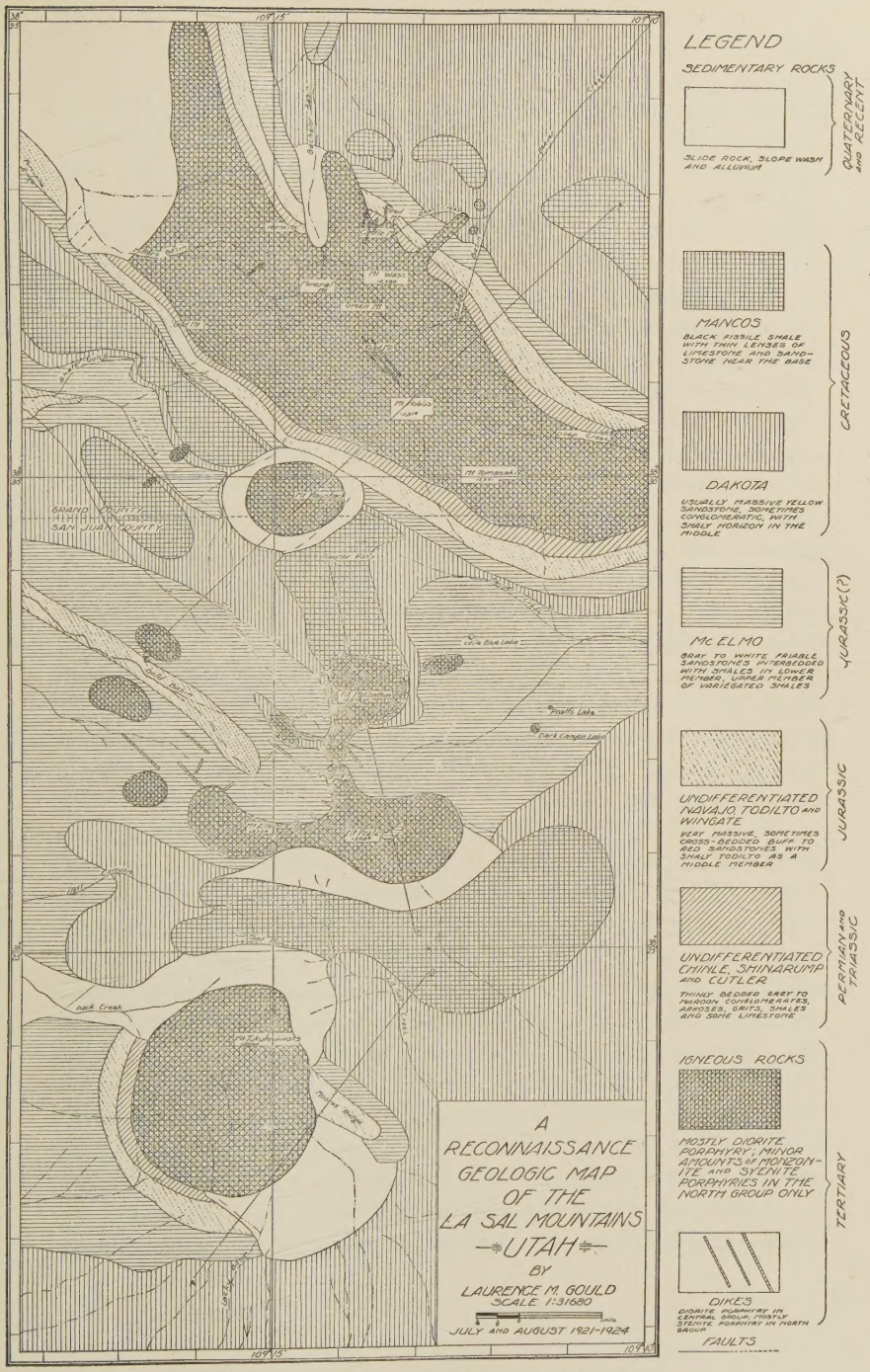
erosional forms typical of semi-arid climates are easily recognized. The buttes and mesas of the Castle Valley region and the rounded dome-like forms of the Navajo sandstone can be clearly identified. On the east or Colorado side of the mountains the bright-colored canyon walls of bare rock surfaces stand out in sharp contrast against the green of the more or less vegetation-covered lands. Sharp or clean-cut profiles like those of the western side are here much less pronounced. It is evident that on this side of the mountains more humid climatic conditions obtain.

PHYSIOGRAPHIC DEVELOPMENT OF LA SAL MOUNTAINS

The Distribution of the Peaks and the Relief

La Sal Mountains as a whole consist of some twenty major peaks divided into three groups (see Map 2). These groups indicate areas of igneous activity and are separated by sedimentary saddles. Geyser Pass divides the north and central groups and La Sal Pass the central and southern groups. These passes are about a mile and a half wide. Most of the peaks are in the north group, which is greater in extent than the other two groups combined; only one major peak is found in the south and only three in the central groups. The central group, however, is considerably higher than either of the end groups and the three peaks here are the highest mountains in the whole region. The upper slopes of the mountains for 2,000 to 3,000 feet are quite precipitous. On the eastern side the lower slopes flatten out gradually and continue into Colorado at the level of the Dakota sandstone. Westward toward the Colorado River the descent from the mountains is more precipitous. The upturned sediments about the igneous cores flatten out very near the mountains proper, but the farther one goes westward from the mountains the greater is the depth to which erosion has proceeded. As a result, one descends by a series of stratigraphic steps, often with enormous treads, from the Mancos shales of Cretaceous age adjacent to the mountains, to the Carboniferous exposed in Moab Valley near the Colorado River. The summits of the


LA SAL MOUNTAINS
—UTAH—
Topography compiled largely from partly completed map and other official records of the U.S. Forest Service-La Sal National Forest.
Data compiled and topography completed by
Ralph L. Belknap
Contour Interval 200 ft
July and August 1921–1924
GRAND COUNTY
SAN JUAN COUNTY
Geyser Pass
Oowah Lake
Dark Canyon Lake
Beaver Creek
Deep Creek
Buffalo Pass
Mill Creek
Olive Gulch
La Sal Pass
La Sal Creek
Rock Creek
Cottonwood Creek
Mill Hollow
Mt. Waldo
Mt. Peale
Mt. Tomasaki
Mt. Mellenthin
Mt. Hayden
Mt. Ruth
Mt. Mellenthin


LEGEND
SEDIMENTARY ROCKS
SLIDE ROCK, SLOPE WASH AND ALLUVIUM
QUATERNARY AND RECENT
MANCOS
BLACK FISSILE SHALE WITH THIN LENSES OF LIMESTONE AND SANDSTONE NEAR THE BASE
DAKOTA
USUALLY MASSIVE YELLOW SANDSTONE, SOMETIMES CONGLOMERATIC, WITH SHALY HORIZON IN THE MIDDLE
CRETACEOUS
MC ELMO
GRAY TO WHITE FRIABLE SANDSTONES INTERBEDDED WITH SHALES IN LOWER MEMBER, UPPER MEMBER OF VARIEGATED SHALES
JURASSIC (?)
UNDIFFERENTIATED NAVAJO TODILTO AND WINGATE
VERY MASSIVE, SOMETIMES CROSS-BEDDED BUFF TO RED SANDSTONES WITH SHALY TODILTO AS A MIDDLE MEMBER
JURASSIC
UNDIFFERENTIATED CHINLE, SHINARUMP AND CUTLER
THINLY BEDDED GREY TO MAROON CONGLOMERATES, ARKOSES, GRITS, SHALES AND SOME LIMESTONE
PERMIAN AND TRIASSIC
IGNEOUS ROCKS
MOSTLY DIORITE PORPHYRY; MINOR AMOUNTS OF MONZONITE AND SYENITE PORPHYRIES IN THE NORTH GROUP ONLY
DIKES
DIORITE PORPHYRY IN CENTRAL GROUP, MOSTLY SYENITE PORPHYRY IN NORTH GROUP
TERTIARY
FAULTS
A RECONNAISSANCE GEOLOGIC MAP OF THE LA SAL MOUNTAINS UTAH
BY LAURENCE M. GOULD
SCALE 1:31680
JULY AND AUGUST 1921-1924
GRAND COUNTY
SAN JUAN COUNTY
Mt Waas
Mt Tomasah
Mt Tukuhnikivats
Pack Creek
Paradox Valley
Dark Canyon Lake
Pinto Lake
Little Blue Lake
Colo. River
Dolores River
Mt Peale
Mt Mellenthin
Mt Hillers
Mt Ellen
Mt Pennell
Mt Tukuhnikivats
Mt Waas
Mt Tomasah

peaks range in height from 11,000 to 13,000 feet. At Moab the Colorado River reaches a level of 4,000 feet. Of this difference in elevation between the mountain tops and the Colorado, fully half is due to the mountain uplift.

Weathering and Erosional Processes

The mountains, including the sedimentary saddles or passes, are so much higher than the surrounding country that the drainage system as a whole is practically radial (see Map 2). The principal streams which drain into the Dolores River are: Beaver Creek, which heads in Beaver Basin of the north group; Rock Creek, which is formed by the junction of Geyser Creek and Deep Creek; and La Sal Creek (Tukuhnikivats Creek of the Hayden Survey map), which heads in La Sal Pass and the south group. The streams which flow directly into the Colorado River are Mill Creek which drains the greater part of the western slopes of the mountains and enters the Colorado by way of Spanish Valley and Castle Creek, which heads in the north group and enters the Colorado through Castle Valley. Though many of the mountain streams are not permanent, those whose courses extend across the surrounding mesas have in many cases cut deep canyons; of these the Mill Creek Canyon (Pl. VI) is the most pronounced.

So far as the surface expression of the north and south groups of the mountains is concerned, the structure has had a profound effect. The shaly or thinly bedded strata adjacent to the igneous centers have eroded more rapidly than either the massive sandstones farther removed or the hard porphyry cores themselves. Hence these two groups present the aspects of gigantic necks surrounded by loosely fitting collars. In some places the mountain streams parallel the neck until an opening across the massive collar is reached. Structural conditions such as those described are lacking in the central group, so that here the higher precipitous mountain slopes merge with the lower slopes with no great breaks and the drainage is quite regularly radial.

Above the vegetation-covered slopes of the mountains the rocks have been so split and broken up by very intensive frost

action that even the peaks and most of the slopes are covered with loose angular blocks sometimes of enormous size.

Glaciation in the Mountains

The effects of the Pleistocene glaciation are still strongly marked in parts of the mountains. This statement applies to the erosional rather than to the depositional features, for the glaciers were very short and except in the central group did not leave deposits which are still very prominent. The heads of the major valleys in the mountains are referred to as 'basins.' The term in this sense usually means a feature much broader than the typical V-shaped valley head formed solely by the erosional work of running water. Most of these so-called basins are cirques. In the north group Miners' Basin, Bachelor Basin, Beaver Basin (Pl. II, Fig. 1) and Deep Creek Basin (Pl. III, Fig. 1) there occur prominent cirques. The glaciers did not extend far enough from any of these cirques to form recognizable U-shaped valleys. In most of them, however, low rounded deposits of morainal character are still preserved. In the central group the glaciers were developed on a larger scale. The head of Horse Canyon, Gold Basin, and the head of Dark Canyon are all well-developed cirques. In Dark Canyon and Gold Basin (Pl. III, Fig. 2), the glaciers have extended far enough from the cirques to form U-shaped valleys, which are still easily identified. Dark Canyon seems to have possessed the largest glacier in the whole mountain area. It not only scoured out the most extensive U-shaped valley, but left morainal deposits of sufficient magnitude to dam up the valley and to form morainal lakes. Dark Canyon Lake is the largest of these. About three fourths of a mile below it lies Pratt's Lake (Pl. IV, Fig. 1), which shows with particular clearness its morainal dam. Little Blue Lake northeast of Mt. Mellenthin is also a morainal dam lake. These three lakes are the only ones that merit the dignity of being so called, but there are numerous other basins, some of which are filled with swamps which owe their existence to glacial deposition.

There is some question whether or not the south group was

glaciated. It is much lower than either of the other two groups and hence may have escaped such action, but Lackey Basin and the basin to the upper right of Pack Creek may be in part the results of glacial erosion.

Rock Glaciers

So-called rock glaciers are found in nearly all the cirques and along some of the valleys. These present a different profile and relief from ordinary talus slides. Rude concentric ridges characterize the lower lobe-shaped fronts which rise rather steeply from the valley floor upon which they appear to be advancing. Capps,[1] who studied similar phenomena in Alaska, believed that such masses were in actual motion because of the formation of interstitial ice. Howe,[2] after studying the same phenomena in the San Juan Mountains, reached the conclusions that the rock glaciers were not in motion and that their present position is due to landslides rather than to any glacier-like motion induced by the formation of ice in the crevices between the rock fragments. The latter theory seems more probable to the author than that of Capps. The best developed rock glacier in all La Sal Mountains is not found in or at the base of a cirque, but at the bottom of a steep valley side (Pl. IV, Fig. 2). The valley side from which the material of this rock glacier came is still so steep that it is difficult to see how it could have reached its present position in any other way than by landslides, as suggested by Howe.

II. The Sedimentary Rocks

No beds older than Permian or possibly Permo-Pennsylvanian are exposed in the immediate vicinity of the mountain uplift. If, however, we consider Spanish or Moab Valley, as it is variously called, as a part of La Sal Mountain province or region, then there is exposed a sedimentary series extending from the Hermosa of Upper Pennsylvanian to the Mancos of Cretaceous. About a mile of strata is included in this series.

[1] Capps, S. R., "Rock Glaciers in Alaska," *Journ. of Geol.*, 18 (1910): 359–375.

[2] Howe, Ernest, *Landslides in the San Juan Mountains, Colorado. Professional Paper, U. S. Geol. Surv.*, No. 67 (1909): 1–58.

Generalized Section of the Rocks Immediately to the West and Northwest of La Sal Mountains

The thicknesses were measured by aneroid

Series	Formation		Thickness (in feet)	Lithological Character
Cretaceous		Mancos	0 to 600	Black fissile shale with thin lenses of limestone and sandstone near base
		Dakota Sandstone	200	Light yellow, sometimes conglomeratic sandstone; sometimes two sandstone members with thin shale between
Jurassic?		McElmo	1000	Grey to white friable sandstones interbedded with shales in lower part; an upper division of variegated shales
Jurassic	La Plata Group	Navajo Sandstone	800	Two massive members of brick-red to white, sometimes cross-bedded sandstone, separated by a thin zone of red shales, occasionally with some limestone; a prominent cliff-maker
		Todilto	0 to 200	Deep red thinly bedded sandstones and shales
Triassic?		Wingate	100 to 200	Massive somewhat cross-bedded deep red sandstone; vertical joints produce a columnar effect; a prominent cliff-maker
Triassic		Chinle		Thinly bedded red to red-blue sandstones and shales
		Shinarump Conglomerate	200	Very thinly bedded greyish-maroon calcareous conglomerates and sandstones
Permian		Cutler	800+	Purple, red, pink and sometimes white conglomerates, sandstones, shales, grits, arkose and earthy limestones

The Pennsylvanian has but a limited exposure, being found only in the bottom of Moab Valley. And here only a small part of the entire formation comes to the surface. As one studies the successively younger formations to the Navajo, he finds that all have an ever increasing area of outcrop. The Navajo sandstone of the Jurassic has the greatest areal distribution and constitutes the chief surface rock in the region between the Colorado River and La Sal Mountains. On the western side of the mountains, formations younger than the Navajo are restricted to the mesas which extend out five to seven miles from the base of the mountains. The youngest rock, the Mancos shale, is preserved only in small patches on the tops of the high mesas and on the saddles between the three groups. East of the mountains erosion has not proceeded as far as on the western side and the Navajo is nowhere exposed, except along canyon walls and where it is upturned about the mountains. The McElmo and, to a much greater extent, the Dakota, cover the surface on this side of the mountains.

The Pennsylvanian and Permo-Pennsylvanian

In the upper (northwestern) end of Moab Valley a thickness of at least 500 feet of grits, sandstones, shales and limestones is exposed along the valley. This series is predominantly sandstone and arenaceous shale, though some of the limestone strata attain a thickness of as much as 40 feet. The limestones are hard blue and blue-grey, especially in the lower part of the exposure. Reddish limestones are found higher up. Not only the limestones of the lower zone, but the sandstones and shales as well, are generally grey. In contrast to this the upper beds are dominantly red. Cross [3] called this series Hermosa. Its division into a lighter-colored zone below and a dominantly red one above is, however, suggestive of a possible separation of the two parts. Recognizing this fact Prommel [4] calls attention to the striking

[3] Cross, Whitman, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Journ. of Geol.*, 15 (1907): 669.

[4] Prommel, H. W. C., "Geology and Structure of Portions of Grand and San Juan Counties, Utah," *Bull. Am. Assoc. Petroleum Geologists*, July–August, 1923, p. 388.

exactitude with which the description of the Rico from the type locality by Cross and Ransome [5] fits the upper portion of this Moab Valley series. He therefore recognizes the upper red portion as the Rico of Permo-Pennsylvanian age and the lower grey members as the Hermosa of upper Pennsylvanian.

The Permian

Because of its predominantly red color and sandy character the Rico is difficult to distinguish from the overlying Permian beds. Lithologically it resembles more closely the Permian above than the Hermosa below. These next younger beds, of Permian age, are the Cutler of the San Juan Mountains or the Moenkopi of the Navajo country. The formation is here mainly a series of thinly bedded maroon, "liver-colored," sometimes purple, conglomerates, sandstones, grits, arkoses, shales and minor amounts of limestone. Though the dominant color of the formation is red, there are lighter-colored horizons, especially in the lower portion. These are grey, greenish or pink grits, arkoses and thin sandstones. Occasional blue-grey or reddish earthy limestones occur with these lighter-colored rocks. The grits are generally friable; some effervesce when treated with dilute hydrochloric acid, which indicates a calcareous cement. Not infrequently the grits and conglomerate beds are three or four feet thick. In one locality a grey grit reached a thickness of from 10 to 12 feet. The upper portions of the formation are generally very thinly bedded and easily eroded. Where properly exposed, they produce a sort of bad land topography (Pl. V, Fig. 2).

The Cutler is locally gypsiferous. On either side of Moab to the east of the Colorado, low rounded hills of gypsum and gypsiferous earth are found along the base of the cliffs that form the valley walls. The upper central part of Castle Valley is covered with a light grey to very white porous gypsum. Together with the steep red-maroon valley walls on either side, this occurrence furnishes a notable display of rock color contrasts. The thick-

[5] Cross, Whitman, and Ransome, F. L., *Rico Quadrangle, Colorado. U. S. Geol. Surv. Atlas,* Folio 130, p. 3.

ness of the gypsiferous part of the formation could not be determined. It is apparently very lenticular, but attains great thicknesses at various places.

The base of the Cutler does not outcrop in Castle Valley nor in the adjacent Colorado Canyon. Its maximum exposure does not here exceed 800 feet. In his Cutler–Moenkopi series, Prommel [6] places 1,300 to 1,400 feet of strata.

The Cutler is separated from the overlying beds by a great unconformity. Less than a mile down the Colorado Canyon from the place where Castle Valley enters, the angular character of this break is clearly shown on either side of the river (Pl. V, Fig. 1). In Moab valley this unconformity is apparent on account of a rapid thickening of the beds toward the northwest.

Although the formations here described as Cutler show many features similar to the Moenkopi of the Navajo country, at no place within the entire area studied is there any equivalent of the De Chelly sandstone. Descriptions of the same series of rocks from Paradox Valley [7] and other localities but a few miles east of the mountains fit the exposures in the immediate vicinity of the mountain uplift so well that it seems desirable to retain the term Cutler for the whole series. To be sure the gypsiferous phase of Moab and Castle valleys has no well-defined equivalents in the San Juan Mountains, nor even in the areas nearer the mountains mentioned above, and it might be well to emphasize the fact that the occurrences of gypsum here described as a part of the Cutler must not be confused with the occurrences of gypsum, gypsiferous shales, and the like, in the bottom of Paradox Valley and in similar localities of western Colorado. Coffin [8] points out that the gypsiferous series in the region of Gypsum Valley are separated from the Cutler by a well-recognized uncomformity. But he further states that considerable quantities of gypsum are found in the red shales of the Cutler itself, though at no place, to judge from the descriptions of the

[6] Prommel, H. W. C., *op. cit.*, p. 389.

[7] Coffin, R. C., *Radium, Uranium, and Vanadium Deposits of Southwestern Colorado. Bull. 16, Col. Geol. Surv.*, 1921, p. 47.

[8] Coffin, R. C., *op. cit.*, pp. 42–43.

sections cited, on a scale comparable to the occurrences in the Moab and Castle valleys. Beds of recognized Permian age carrying gypsum have been described from many widely separated localities in the western states. It is so often not a persistent member that its absence or presence in adjoining areas, such as La Sal Mountain region and the neighboring parts of Colorado, can hardly be considered significant enough to prevent the correlation of otherwise similar beds.

The Triassic Formations

Overlying the Cutler is a series of very thinly bedded maroon or greyish-maroon, partly calcareous conglomerates. The presence of light-colored pebbles accounts for the greyish cast of the rock. These beds are the "saurian conglomerate" of Colorado. In his reconnaissance trip through this region Cross [9] noted the occurrence of fragments of bones and teeth of crocodilian or dinosaurian animals in this member. Some two hundred feet above this conglomerate in Castle Valley comes the massive Vermilion Cliff or Wingate sandstone. The rocks in between evidently do not all belong to the conglomerate series at the base. Indeed the upper portion consists of thinly bedded sandstones and arenaceous shales, in their lithological character, resembling much more closely the massive sandstone above than the conglomerate below. Further, this member thickens perceptibly toward the south. These two series of rocks are believed to be the equivalents of the Shinarump conglomerate and the Chinle of southeastern Utah.

The Dolores of the San Juan Mountains and western Colorado seems to be equivalent to this entire series of conglomerates, sandstones and shales, together with the massive rock at the top which is variously known as the Wingate or the Vermilion Cliff sandstone. Gregory [10] includes the Wingate and Todilto together with the Navajo as the equivalents of the La Plata group of the San Juan Mountains, and places the Shinarump conglomerate

[9] Cross, Whitman, p. 652 of paper cited in note 3.

[10] Gregory, H. W., *Geology of the Navajo Country. U. S. Geol. Surv. Prof. Paper,* 93, p. 16.

and the Chinle formations as the approximate equivalents of the Dolores. Cross [11] in his paper on the *Red Beds* suggests that the Dolores of Colorado includes diminished equivalents of the Shinarump group and Vermilion Cliff sandstone of the plateau province. This view, with some exceptions or qualifications in the case of the Shinarump, was further substantiated by him on his reconnaissance [12] through the then Grand River region of Utah just west of La Sal Mountains. Furthermore the Dolores of western Colorado, only a few miles to the east of La Sals, as described by Coffin,[13] clearly includes the massive member (Vermilion Cliff or Wingate), at the top, together with the formations below, which have been called in this paper the Shinarump conglomerate and the Chinle. Coffin, therefore, considers this massive member as the top of the Triassic. Gregory [14] places the Jurassic-Triassic contact, with a question mark, between the Chinle and the Wingate. Mehl's [15] paleontological studies in the vicinity of Ft. Wingate, New Mexico, would, apparently, place this massive sandstone member in the Triassic, thus raising the Jurassic-Triassic contact to the top of the Wingate; in other words the top of Coffin's Dolores as described from areas in Colorado a few miles to the east of La Sal Mountains.

Regardless, however, of the more exact delimitation of the ages and correlation of these various formations, the more detailed and definitive nomenclature of apparently equivalent strata in southeastern Utah seems more applicable and more desirable than the retention of the name Dolores for so great a thickness of beds that lend themselves rather easily to further subdivision.

In Plate V, Figure 2, the lower bench represents the probable lower level of the Shinarump conglomerate. Below lies the

[11] Cross, Whitman, and Howe, Ernest, *Red Beds of Southwestern Colorado and Their Correlation. Bull. Geol. Soc. Am.*, XVI (1905): 496.

[12] Cross, Whitman, p. 650 of paper cited in note 3.

[13] Coffin, R. C., *op. cit.*, pp. 47–51.

[14] Gregory, H. E., *op. cit.*, p. 17.

[15] Mehl, M. G., Toepelmann, W. C., Schwarts, C. M., *New or Little Known Reptiles from the Triassic of Arizona and New Mexico with Notes on the Fossil Bearing Horizons near Wingate, New Mexico. Bull. Univ. of Okla., New Series*, No. 103, Univ. Series No. 5, March, 1916, pp. 29–32.

Cutler and above, the Chinle, capped by the Wingate. A comparison of this plate with Plate VII, Fig. 1, of *Professional Paper 132,* which illustrates Castle Butte near the mouth of Red Canyon in the San Juan Canyon region, suggests similarities or relationships between the formations indicated too evident to need comment.

The Wingate is a massive somewhat cross-bedded, red-brown rather than vermilion sandstone. In Castle Valley and the general region to the northwest of La Sals it is peculiarly important as a capping for buttes and mesas along which it characteristically outcrops in sharp cliffs. Remarkably well developed vertical joints give the cliffs a columnar effect and frequently cause them to weather into spines or castle rocks (Pl. I, Fig. 1, and Pl. V, Fig. 2).

The Jurassic Formations

Above the Wingate is a series of thinly bedded sandstones and arenaceous shales so like the massive cross-bedded rock below that it might almost be regarded as a shaly phase of the Wingate itself. This member is, however, persistent, sometimes attaining a thickness of nearly two hundred feet. It may, therefore, be considered a separate formation from the Wingate below, and on account of its position between the easily recognized Wingate below and the equally evident Navajo above may safely be designated as the Todilto, which occupies the same stratigraphic position in southeastern Utah.

Of all the formations that have affected the topographic expression of the plateau country to the west and to the south of La Sal Mountains none has played so important a rôle as the Navajo sandstone (the La Plata of the San Juan Mountain region). Most of the fantastic forms that give so much charm to this region are carved from the massive Navajo (Pl. I, Fig. 2).

In many of the places studied, if the major part of the formation is still preserved, it is recognizable in its tripartite divisions, a lower and an upper massive series separated by a thin zone essentially of red shales with now and then some limestone. The lower part consists of massive brick-red to buff sandstones which

in places attain a thickness of four hundred feet. Bedding planes are notably absent. Not infrequently thicknesses of one hundred feet or more in which no indications of bedding planes may be found are exposed along the canyon walls. Particularly good exposures of this member are found along the canyon walls of Mill Creek. These walls are so blackened in places that they seem to have been painted. This effect is produced by a thin rind of desert varnish.

The upper member of the Navajo is a fine even-grained massive sandstone, frequently strongly cross-bedded. It is yellow-brown to orange for the greater part, becoming pink and lighter toward the top. In places the top portion of fifty to one hundred feet is practically white. It is this member of the Navajo that is locally so characteristically weathered into caves, alcoves, arches and numerous other fantastic forms. Small pockets also are common and frequently give to the rock a roughened or pitted surface.

Its massive character makes the Navajo everywhere a cliff-maker, but not with the sort of expression displayed by the Wingate. The Navajo is generally friable, so that particularly where there is no overlying formation its steep walls terminate in rounded forms rather than in sharply angular forms exhibited by the Wingate.

On the so-called sand-flat between the Colorado and the mesas at the foot of the mountains, the Navajo is the chief surface rock (Pl. II, Fig. 2). Its occasional complex cross-bedding, together with its massive character and easy erodibility, have here produced a maze of erosion forms of unusual beauty. In many parts of the region excessive weathering and erosion along the joints have produced the elongated dome-like forms that from a distance so largely dominate the landscape. After the torrential desert rains, these rocks glisten in the sun; they are difficult to cross, hence the local name of "slick rock." These rounded forms are easily recognized from the peaks of La Sals. Because of their frequent and regular occurrence Peale,[16] who

[16] Peale, A. C., *U. S. Geol. and Geog. Surv. of the Territories. 10th Annual Rept. for 1875*, 1877, p. 62.

saw them from the mountains, thought they might be "sheep backs" of glacial erosion. Closer observation by Dr. Peale would no doubt have demonstrated their real origin.

The Jurassic (?) and Cretaceous Formations

The formations above the Navajo, i.e. the McElmo, the Dakota and the Mancos, constitute the fairly gentle vegetation-covered slopes from the mesa rims on the west to the foot of the mountains. Furthermore all three formations are generally easily eroded, so that their intimate relationships are rather obscure. Neither the McElmo-Dakota nor the Dakota-Mancos contacts were definitely located. On the basis of observations with an aneroid the thickness of the McElmo was estimated to be about 1,000 feet, the Dakota 200 feet, and the Mancos shale from 0 to 600 feet.

In a general way the McElmo may be divided into two parts, a lower which consists of sandstones separated by arenaceous shales, and an upper which is predominantly shales. A dense fine-grained reddish sandstone showing vertical jointing similar to the Wingate constitutes part of the mesa rim rock (Pl. VI). Though this member is quite unlike the recognized McElmo sandstone ledges above, it is believed to be here the basal member. In places the Navajo is directly overlaid by a shaly zone containing limestones and chert. But the dense red rim rock seems not to be separated from the Navajo by a well-defined shaly zone.

The other sandstone members of the McElmo are light grey to white. They are loosely cemented, calcareous material often constituting the binding material, and are therefore easily eroded. Occasionally a thin indurated surface gives the rock a pinkish or even darker tinge and makes it also much more resistive to erosion. This lower sandstone part of the McElmo is also characterized by beds of hard blue limestone and chert. On Wilson Mesa the early settlers burned this blue limestone to make lime. Fragments of chert are scattered over the surface in many places, but no beds greater than a few inches in thickness were found. Prospectors bring reports of a great bed of

"chalcedony quartz" almost a hundred feet thick near the south group of La Sals. There was no opportunity to verify this story.

Pieces of silicified wood are not uncommon on the lower parts of the mesas, and fossil bones, which are probably saurian, were noted below Boren Mesa.

The upper part of the McElmo is one of the most vivid and individual horizons about the mountains. A great series of so-called "variegated shales" forms this portion of the formation. Green, blue, red, lavender and purple (with the lavender and purple predominating), together with grey, constitute the base from which the curiously mottled colors of these beds are produced. Varying grades of purity from very arenaceous shales to those which become plastic and slump when wet are represented in these shales. Exposures from slumping along the green vegetation-covered slopes present color displays that are fairly dazzling. When hammered these shales break into small angular fragments, but do not show any tendency toward fissility.

In contrast to the reddish rocks below, which dominate the landscape to the west of the mesas, the Dakota sandstone is light yellow to buff. The yellowish color is due to limonite which is sometimes so distributed in small patches that the freshly fractured surface presents a "freckled" aspect. Generally the Dakota is friable, but in places is indurated and takes on a pinkish coloration.

The lower part of the formation is conglomerate. The small gravel-sized pebbles of quartz, quartzite and chert, which constitute the conglomerate, are not distributed as definite beds but occur as lenses, which suggests a fluviatile origin.

East of the mountains from Geyser Pass the Dakota is easily recognized in its triple division, a lower and an upper massive zone separated by a shaly zone. The shale is carbonaceous and occasionally carries low-grade coal. There is such an occurrence east of Geyser Pass, which in the earlier prospecting days in the mountains was mined by the prospectors for use in their forges.

In places the Dakota is not easily recognizable, for at times

it shows a surprisingly rapid transition from the characteristic occurrence noted above to more thinly bedded strata.

It is because of the extreme facility with which the formations above and below are eroded, and not because of inherent qualities of resistance to erosion, that the Dakota is often a singularly conspicuous formation near the mountains. It stretches away from the eastern foot of the mountains to constitute the main cover rock for much of the eastern edge of Utah and of western Colorado. When upturned about the eruptive centers of La Sals, it frequently forms particularly striking hogbacks (Pl. VIII, Fig. 1).

A few feet above easily recognized Dakota beds below Bald Mesa there was found an exposure of slate-colored to black shale. Thin lenses of blue limestone and some sandstone were found at this horizon. Numerous fossils were collected of which the following species have been identified: *Gryphaea newberryi; Inoceramus dimidius; Baculites gracilis; Scaphites warreni.* This is apparently the Mancos shale. Exposures higher up along the mesa show it to be predominantly a drab to black fissile papery shale. It erodes easily and when wet becomes very plastic. Its surface expression is, therefore, frequently a bad-land sort of topography.

Nowhere about the mountains does the Mancos exist in its full development. It is preserved in small patches northeast of Beaver Basin, on both La Sal and Geyser passes, and caps Boren and Bald Mesas. It attains its greatest thickness at the last named locality.

Pleistocene, Quaternary and Recent Deposits

As a result of the glaciation of the higher mountain valleys during the Pleistocene age some glacial deposits were formed. Most of the glaciers were short, so that the only deposits now recognizable are a few short moraines. Such deposits are found in the various basins of the north and central groups. The best preserved forms are those in the vicinity of Dark Canyon Lake and Pratt's Lake (Pl. IV, Fig. 1), which lie along the flat eastern slopes of the central group.

In many places the lower slopes of the steeper mountains are

covered by great accumulations of slide rock, sometimes in quantities so great that they completely obscure the structural relationships with the surrounding regions.

Varying amounts of slope wash and alluvium are found about all three groups. The heads of the valleys, or the basins so called, are frequently filled with immense thicknesses of such materials. The deposits consist of both fine and coarse clastic materials showing little or no tendency toward assortment. The contained pebbles are subangular, which indicates transportation over but short distances. The upper parts of Castle Valley and Miners' Basin are covered with at least 200 feet, and perhaps much more, of such detritus. Recent gullying in other basins of the north group, but particularly in those about the south group, namely Pack Creek, Pole Canyon, and Lackey Basin, demonstrates the existence of equally great thicknesses of alluvium and slope wash in these basins.

Projecting out into Castle Valley toward the northwest as a spur from the lowest exposed igneous part of the north group is a conglomerate ridge which divides the upper part of the valley into two parts. It consists largely of subangular pebbles of porphyry so loosely cemented together that the rock crumbles easily under a blow from the hammer.

Figure 1 illustrates the relationship which the sediments of La Sal Mountain region bear to those of adjacent parts of Utah and neighboring portions of Colorado and Arizona. The geographic locations of the columnar sections shown in this figure are indicated on the map (Map 1). The sections are compiled from the following sources:

1. *Rock Formations in the Colorado Plateau of Southeastern Utah, and Northern Arizona*, by C. R. Longwell, H. D. Miser, R. C. Moore, Kirk Bryan and Sidney Paige. *U. S. Geological Survey, Professional Paper*, No. 132 A, 1923, Plate II, Section 11.

2. *The Geology of the Navajo Country*, by H. E. Gregory. *U. S. Geological Survey, Professional Paper*, No. 93, 1917.

3. *Geology and Structure of Portions of Grand and San Juan Counties*, Utah, by H. W. C. Prommel. *Bulletin of the American Association of Petroleum Geologists*. Vol. VII, No. 4, July–August, 1923, Plate III. It will be noted that the names of the formations for this section follow the

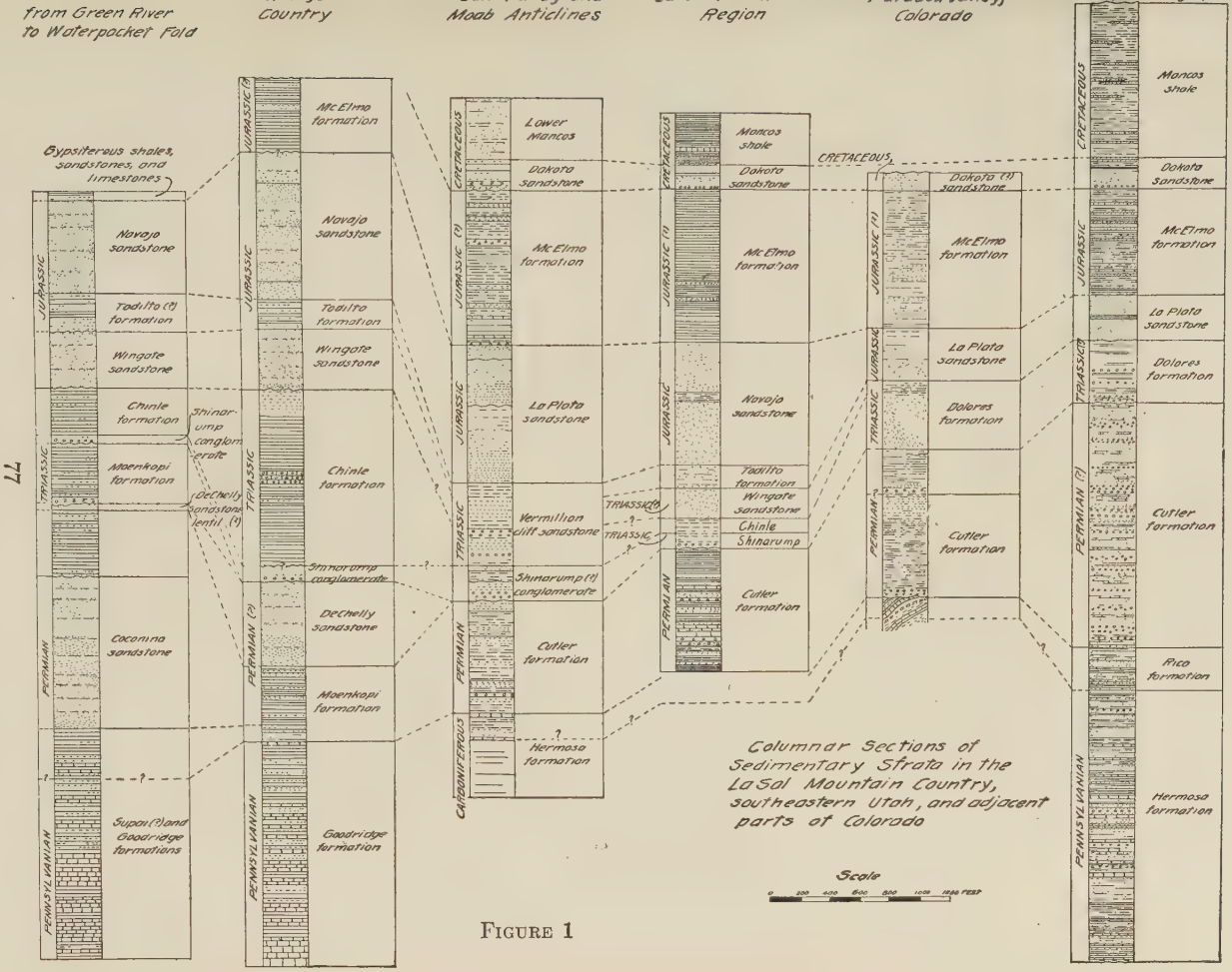

from Green River to Waterpocket Fold
Country
Moab Anticlines
Region
Colorado
Gypsiferous shales, sandstones, and limestones
Navajo sandstone
Todilto (?) formation
Wingate sandstone
Chinle formation
Shinarump conglomerate
Moenkopi formation
DeChelly sandstone lentil (?)
Coconino sandstone
Supai (?) and Goodridge formations
JURASSIC
TRIASSIC
PERMIAN
PENNSYLVANIAN
McElmo formation
Navajo sandstone
Todilto formation
Wingate sandstone
Chinle formation
Shinarump conglomerate
DeChelly sandstone
Moenkopi formation
Goodridge formation
Lower Mancos
Dakota sandstone
McElmo formation
La Plata sandstone
Vermillion cliff sandstone
Shinarump (?) conglomerate
Cutler formation
Hermosa formation
CARBONIFEROUS
Mancos shale
Chinle
Shinarump
CRETACEOUS
Dakota (?) sandstone
Dolores formation
Rico formation
Columnar Sections of Sedimentary Strata in the La Sal Mountain Country, southeastern Utah, and adjacent parts of Colorado
Scale

FIGURE 1

older nomenclature of the plateau country. In the text, however, Prommel correlates the Permian, Triassic and Jurassic formations with those of southeastern Utah and adopts almost entirely the nomenclature of the Navajo country.

4. Generalized section of the rocks exposed in Castle Valley and along the canyon of the Colorado, north and west of La Sal Mountains, as studied by the author.

5. *Radium, Uranium and Vanadium Deposits of Southwestern Colorado*, by R. C. Coffin. *Bulletin 16, Colorado Geological Survey*, 1921, Plate LV, page 31.

6. *The Rico Quadrangle, Colorado*, by Whitman Cross and F. L. Ransome. *U. S. Geological Survey Atlas*, Folio 130. Generalized Section of Strata in the Rico Quadrangle, by Whitman Cross and Arthur C. Spencer.

III. The Igneous Rocks

Evidence of igneous activity in the mountains is preserved principally as the cores of the three separate groups and as the igneous butte, Little Round Mountains, which lies out in Castle Valley about five miles northwest of the northern group. The latter occurrence is about two miles beyond the border of the area covered by the geological map (Map 3). In addition to these major igneous features a few radial dikes are found in connection with the central group; two small flows or former sheets are known, one as a cap for the lower end of the ridge north of Gold Basin and the other a mile west by northwest of Mt. Haystack. This last occurrence is cut into two parts by the canyon of Mill Creek. Dikes on either end of this bisected mass probably represent the conduits from which the magma came. Finally there is in the north group a number of strongly alkalic dikes which indicate a period of activity subsequent to that of the main intrusion. These dikes are injected into a more alkalic phase of the main intrusive than is elsewhere found. In some places they cut into the surrounding upturned sediments.

All the rocks have a porphyritic texture and in those from the main intrusive mass they are universally characterized by recognizable phenocrysts of feldspar. All the rocks belong to the hypabyssal members of those igneous rocks which are distinguished by the kind of feldspar that predominates. Their

relationships to their plutonic and extrusive equivalents may be indicated thus:

PLUTONIC	HYPABYSSAL	EXTRUSIVE
syenite	syenite porphyry	trachyte
monzonite	monzonite porphyry	latite
diorite	diorite porphyry	andesite

Iddings[17] delimits the three plutonic groups on the basis of the predominating feldspar as follows: 1. Syenites, in which alkali feldspars exceed lime-soda feldspars by more than 5 to 3; 2. Monzonites, in which the alkali feldspars and the lime-soda feldspars vary within the proportions 5 to 3 and 3 to 5; 3. Diorites, in which the lime-soda feldspars exceed the alkali feldspars by more than 5 to 3.

In the determinations of the names to be applied to the rocks of La Sal Mountains, these proportions of the feldspars have been followed as carefully as possible. In fifty thin sections examined, representatives from all three of the hypabyssal groups were recognized. Most of the rocks of the major intrusion are characterized by phenocrysts of plagioclase and very few or none of orthoclase. They are very evidently diorite porphyries. The monzonite and diorite facies are localized, as will appear later.

Occurrence of the Various Types

The southern and central groups, including the radial dikes, Little Round Mountain, the dikes and flow west of Mt. Haystack and most of the north group of the mountains are composed of diorite porphyries.

Only in the northern group is there much evidence of magmatic differentiation. Mineral Mountain represents an area constituted of a particularly clear type of syenite porphyry. As one proceeds from this apparent center of the alkalic phase of the intrusion, there is a gradual decrease in the alkalic feldspars. Green Mountain is very clearly a monzonite porphyry. Sections examined from other adjacent localities demonstrate that parts, at least, of Mts. Waas, Castle and Hobbs are also of monzonite

[17] Iddings, J. P., *Igneous Rocks*, II: 150.

porphyry. The megascopic recognition of most of the monzonite porphyries was of course not possible and the number of slides studied was insufficient to enable one to delimit more exactly this phase of the intrusion.

The small igneous cap on the lower end of the ridge north of Gold Basin is a syenite porphyry differing essentially from that of Mineral Mountain only in texture.

Reference has been made to the fact that associated with the more alkalic phase, just noted, are a number of dikes. These dikes are found principally in two areas; one in Beaver Basin where there are three dikes which have an average strike of N. 40° W.; the other in Bachelor Basin, chiefly in association with Castle Mountain. The dikes in the latter locality have an average strike of N. 15° E. All these dikes are short and most of them were but a few feet in thickness. They represent various facies of syenite porphyries, differing in all cases from the more widely distributed Mineral Mountain and Gold Basin occurrences.

A very different type of rock is that represented by great slides about one half-mile west of the former town of Basin, in Miners' Basin. Though a definite outcrop could not be found, this rock is so different in appearance from the adjacent diorite porphyry that it is believed to be a dike rock. It is a rhyolite porphyry.

THE PETROGRAPHY OF THE INTRUSIONS

Diorite Porphyry

Megascopic appearance. — At first glance the diorite porphyry is seen to be a dense light-grey to white rock with black specks irregularly scattered through it. Closer examination shows that the black specks are phenocrysts of hornblende (many of them acicular in development) which, together with numerous light-colored tabular phenocrysts of feldspar, are imbedded in a light-grey aphanitic ground-mass. Light green phenocrysts of pyroxene are found, but are everywhere much less numerous than the hornblende. Phenocrysts of quartz are only occasionally found. Hornblendic inclusions sometimes measuring as much as four or five inches in length were noted from a few localities.

In some places these grade into the surrounding mass. Careful examination shows that these inclusions consist of the same kind of materials as the main porphyry mass, but are developed on a different scale. Emery [18] describes hornblendic inclusions from the diorite porphyries of Carrizo Mountain which appear to be identical with these noted in La Sal Mountains.

Microscopic description. — Many broad tabular idiomorphic phenocrysts of plagioclase, usually with Albite twinning and often with Carlsbad twins as well, dominate the microscopic appearance of the rock. Most of the plagioclase is oligoclase, andesine, or gradations between the two; more alkalic or more calcic varieties being rare. Zonary banding is common; in one specimen fourteen distinct bands could be noted.

Orthoclase phenocrysts are sparingly distributed or even entirely lacking in the diorite porphyries and when present are always found in smaller crystals than the plagioclases. Most of it shows an elongated rather than a broadly tabular development. Carlsbad twins are common.

Hornblende of the common green pleochroic variety is the characteristic ferro-magnesian mineral. In a few slides there is a little brown hornblende, and in others some bluish-green varieties are noted. Idiomorphic outlines and acicular crystals, many of them with imperfect terminal faces, are common (Pl. VII, Fig. 1). Twinning is frequently noted in the elongated forms. In some places the hornblende is in intimate association with magnetite; in others it encloses magnetite crystals, and again it may be almost completely filled with tiny grains of magnetite, or surrounded by black magnetite borders.

Pyroxene is present in many of the specimens, though usually in amounts subordinate to the amphibole. It commonly shows an idiomorphic development and is frequently twinned. It is usually a pale green to colorless augite (Pl. VII, Fig. 2), though a few varieties from diposide to aegerine were found. Of these aegerine augite is next in importance to the augite.

In four or five slides small amounts of brown strongly pleo-

[18] Emery, W. B. "The Igneous Geology of Carrizo Mountain," *Am. Journ. of Science*, XLII (1916): 356–357.

chroic biotite were found. Even in the same rocks, however, the amphibole was far in excess of the mica.

Although quartz is a characteristic associate of the feldspar in the ground-mass, it is not common as a phenocryst. In only two or three specimens was it present in sufficient amounts to enable one to designate the rock a quartz-diorite-porphyry.

The most characteristic of the accessory minerals is magnetite, which in many specimens is present in two generations. Though not present in amounts so large, titanite is almost as widespread as magnetite. It is developed in long slender crystals which frequently show twinning. Apatite occurs in all the rocks, usually as tiny needles. Zircon, always as tiny grains, is very sparingly distributed in them.

The ground-mass is microcrystalline and consists almost entirely of allotriomorphic quartz and feldspar, usually orthoclase. Considerable variations in the texture of the ground-mass were noted, some specimens approaching on the one hand a coarsely micro-granular texture akin to their plutonic relatives, while others have a very finely holocrystalline ground-mass typically andesitic or trachytic. Fluxion structure was rarely found in the microscopic sections.

In some specimens the rocks were so badly altered that in thin section they presented a dusty or dirty appearance, often making their exact identification questionable. The feldspars were commonly found altering to sericite and to a lesser extent to calcite. Secondary calcite was widely developed in some specimens. In at least two slides the ferro-magnesian minerals were entirely lacking, but epidote was present in considerable quantities. It is sometimes the colorless variety, but more often the greenish pistacite with brilliantly speckled interference colors. In a few slides leucoxene was found. Small amounts of a fibrous material which may be the fibrous amphibole, uralite, were found in two or three slides.

Monzonite Porphyry

Megascopic appearance. — To the naked eye the monzonite facies present no essential differences from the diorite porphyries.

In some places, as on Green Mountain, phenocrysts of orthoclase can be distinguished. Though hornblende is present, pyroxene is usually the dominant ferro-magnesian constituent.

Microscopic description. — Phenocrysts of orthoclase and plagioclase in relatively even amounts characterize these rocks. Both occur in well-developed tabular crystals with idiomorphic outlines. Carlsbad twinning is common in both and of course in the plagioclase, which is most often oligoclase and albite-oligoclase, albite twinning is common. In a few specimens perthite is almost well enough developed to be called a phenocryst. It is commonly found, however, only in the ground-mass.

Both pyroxene and hornblende of the green pleochroic variety are found. The pyroxene is commonly aegerine augite and is often twinned. The same accessory minerals that characterized the diorite porphyries occur also in these rocks.

Considerable variation is exhibited in the ground-mass of the specimens referred to this type of rock. Some are micro-granular and consist of about equal amounts of quartz and feldspar. Others, as those from Green Mountain and near by in Bachelor Basin, consist mostly of quartz, sometimes quite coarsely crystalline. In another specimen from Mt. Waas, identified as a monzonite porphyry, the ground-mass is of microperthite.

Syenite Porphyry

Megascopic appearance. — Some of the syenite porphyries closely resemble the types just discussed, while others, as that from Mineral Mountain, have a decidedly individual appearance. This rock has the general greyish-white color of the other types, but is seen to consist of numerous light-grey to white phenocrysts of feldspar crowded into a slightly darker ground-mass.

The tabular feldspars are evidently orthoclase and are especially prominent both on account of their light color and their size; a number of them have dimensions as great as 11 by 17 millimeters. A dark greenish pyroxene is also a noticeable phenocryst.

Toward Bachelor Basin or toward the northwest the large prominent orthoclase phenocrysts disappear and the rock more closely resembles the monzonite and diorite porphyries.

The Gold Basin occurrence of syenite porphyry shows a rock quite different from that of Mineral Mountain. In this rock pink phenocrysts of orthoclase, sometimes as large as those in the Mineral Mountain occurrence, are scatteringly distributed in a rather dark-grey ground-mass. Upon careful examination the ground-mass is seen to consist of lath-shaped crystals showing a decided fluxion structure.

Microscopic description. — The large phenocrysts in the Mineral Mountain specimens are found to be entirely orthoclase.

Most of the ferro-magnesian minerals are pyroxene, of which aegerine augite is the most important. Small amounts of a greenish-blue hornblende, which may be the soda-amphibole, catophorite, are also found. Magnetite and titanite in slender-twinned crystals are common. Apatite is present as small needles and as crystals almost big enough to be phenocrysts. The ground-mass, which is cryptoperthite, shows a subparallel arrangement.

In some of the more even-textured varieties a little way from the top of Mineral Mountain the rock is found to consist almost entirely of perthite and cryptoperthite. In other specimens the ground-mass is micro-granular and the phenocrysts are entirely of orthoclase. In one specimen enough hypidiomorphic quartz was found to enable one to designate the rock a quartz-syenite porphyry.

In the Gold Basin type the phenocrysts are found to be entirely orthoclase, frequently with Carlsbad twins. Both the phenocrysts and the cryptoperthitic ground-mass show a subparallel to parallel arrangement. In addition to small phenocrysts of aegerine augite, needles which are probably aegerine are scattered through the ground-mass. Magnetite, ilmenite and a hexagonal section with platy to fibrous structure, which may be zeolite altered from sodalite, are also found.

These syenite porphyries do not represent well-defined or unquestioned types. They show the most pronounced affinities for pulaskite or nordmarkite, and on account of their porphyritic texture may be designated pulaskite or nordmarkite porphyries.

Syenite Porphyry Dikes

Of the three dikes in Beaver Basin the two outer ones are quite similar both megascopically and in thin section. They consist of a greenish-grey ground in which are imbedded rhombic to elongated tabular phenocrysts of orthoclase, commonly measuring from 5 to 7 millimeters. Microscopically these rocks are found to consist principally of alkali feldspars (almost entirely orthoclase) as phenocrysts, set in a microperthitic ground-mass. Small amounts of greatly altered hornblende with a bluish-green color may be arfvedsonite. One slide contained phenocrysts of melanite garnet. Tiny needles of aegerine are crowded into the ground-mass which also contains small amounts of magnetite and titanite. Because of their aplitic (syenitic) character these dikes may be designated as syenite-aplite porphyries.

The third Beaver Basin dike, which lies between the two just described, is a light greenish-grey fairly aphanitic rock; no notable phenocrysts are visible. In thin section it is found to consist of phenocrysts of orthoclase (often apparent only in outline, the interior being filled with tiny needles of plagioclase feldspar), smaller phenocrysts of plagioclase and corroded quartz with inclusions, all set in an allotriomorphic ground-mass of quartz and feldspar. Both orthoclase and plagioclase feldspars are found in the ground-mass. Needles of aegerine are scattered through it. This rock might be classed either as a quartz-tinguaite porphyry, or as a grorudite porphyry.

Another unusual rock consisting of a bluish ground scatteringly speckled with small white feldspars was collected from the same locality as the dikes described above. This rock departs so widely from the country rock of the region that it seems likely that it is also a dike rock. I believe it is the same rock that Prindle [19] described as aegerine-granite porphyry, for in thin section it is found to have a fairly even subgranular texture and to consist almost entirely of quartz and feldspar, chiefly

[19] Clarke, F. W., *Analyses of Rocks and Minerals from the Laboratory of the U. S. Geol. Surv. Bull. 419, U. S. Geol. Surv.*, p. 120.

orthoclase. Much secondary calcite makes the further identification of the mineral constituents questionable. A few small phenocrysts of pyroxene and some epidote are sparingly distributed through the rock and tiny needles, which are probably aegerine, are found in small amounts in the ground-mass. Magnetite occurs in very small amounts.

The principal dike in Bachelor Basin is a strikingly "dappled grey" rock which cuts from the northern slope of Castle Mountain across the gully into the upturned sediments that constitute Red Mountain. The spectacular appearance of this dike is due to the presence of large zonally banded phenocrysts of orthoclase, which commonly attain a length as great as one and three-fourths inches. These, together with small phenocrysts of pyroxene, are set in a greenish-grey aphanitic ground-mass. In appearance this rock suggests an orbicular diorite. On either side of this dike are a number of smaller tabular outcrops which differ mainly in the orthoclase phenocrysts, which lose their zonary banding and take on an elongated tabular shape. In thin section most of the pyroxene is seen to be aegerine, though a few zonally banded pheno-crysts were found which showed gradations from augite to aegerine. Phenocrysts of noselite are found also in considerable number. Frequently this sodalite is found altered to zeolite. Magnetite was noted only in very small amounts. The ground-mass is found to be microperthite clouded by tiny needles of aegerine. Fluxion structure with eddies about the phenocrysts is characteristic of this ground-mass. Secondary calcite and sericite often give the rock a cloudy aspect. The most nearly applicable name for this rock seems to be noselite-tinguaite porphyry.

Cutting clear through Castle Mountain is a narrow dike which megascopically resembles very closely the grorudite porphyry of Beaver Basin. Microscopically it is found to contain more aegerine, less plagioclase in proportion to the orthoclase, and less quartz as phenocrysts, but much more in the ground-mass. This rock shows about equal affinities for the porphyritic facies of grorudite, tinguaite and sölvsbergite.

Near the northwest end of Castle Mountain is a dike with a

blue-grey ground-mass in which are embedded light-colored phenocrysts of orthoclase which commonly show a rhombic outline. These characteristic phenocrysts of orthoclase stand out against their blue ground suggesting grains of wheat, hence the local name coined by prospectors, "wheat grain porphyry."

Under the microscope the phenocrysts are found to be in part perthite, as well as orthoclase. A few oligoclase andesine phenocrysts were also noted. Pyroxene is rare, but epidote is developed in considerable quantities. Magnetite, apatite and ilmenite are common and a small amount of zeolite indicates that sodalite is also present. The ground-mass of this rock is of fine cryptoperthite. Though it suggests in its megascopic appearance a rhombenporphyry, a more accurate name for it seems to be laurvikite porphyry.

The huge slides in the western part of Miners' Basin, referred to above as rhyolite porphyry, show a light-grey to white rock, when not weathered. The weathered surface is grey to yellowish. Perfectly developed prismatic crystals of orthoclase are seen throughout the rock and may be collected in great numbers from the ground, where they have fallen as they weathered out of the parent rock. Quartz in rounded or corroded grains is also a very evident phenocryst. In thin section a few phenocrysts of albite and a little magnetite are also found. The ground-mass is very finely micro-granular.

From the south side of Castle Mountain the writer collected some specimens of a very fine grained slaty-colored rock which seems to be a dike. No individual grains could be detected with the naked eye and even in thin section the rock was found to be so fine-textured as to defy classification. Much grey calcite obscures the major part of the rock, which seems to consist of about equal amounts of allotriomorphic quartz and a turbid feldspar.

A similar rock but lighter in color and even more finely grained was collected from Mt. Tukunikivats. In thin section it appears to be the same sort of rock as the one from Castle Mountain. It seems inadvisable to attempt to classify these rocks without a chemical analysis.

PLACE OF LA SAL MOUNTAIN INTRUSIVES IN THE QUANTITATIVE CLASSIFICATION

From Prindle's collection a rock collected two miles west of Mt. Peale was analyzed by Hillebrand [20] and placed by Prindle as akerose. The writer has examined a number of thin sections from this same general region and all appear to be fairly typical of the diorite porphyry, which constitutes the major part of the intrusive mass. The following analysis from Hillebrand probably represents, therefore, the general composition of the main igneous masses:

SiO_2	61.21
Al_2O_3	17.10
Fe_2O_3	2.72
FeO	1.88
MgO	1.47
CaO	4.83
Na_2O	5.66
K_2O	3.00
H_2O at 105	.34
H_2O above 105	.68
TiO_2	.51
ZrO_2	.02
CO_2	none
P_2O_5	.24
SO_3	none
Cl	.04
MnO	.15
BaO	.13
SrO	.07
Li_2O	trace?
Total	100.05

RELATION OF THE SIERRA LA SAL INTRUSIVES TO THOSE OF OTHER LACCOLITHIC AREAS

The nomenclature of petrography has changed so greatly in recent years that the names used here look little like those employed by earlier investigators to describe the same rocks. This statement is generally true for the other laccolithic areas of this

[20] Clarke, F. W., pp. 120–121 of work cited in note 19.

region. Gilbert[21] identified his Henry Mountain rocks as "porphyritic trachyte." La Sal Mountain intrusives[22] were also first referred to as "porphyritic trachytes." Emery[23] has pointed out that the rocks of the Carrizo Mountain intrusion were called "trachyte" by Holmes and his contemporaries, and that the same rocks were later designated "hornblende porphyrite" by Cross. He further points out that the "hornblende porphyrite" of Cross is the "diorite porphyry" of American petrographers of today.

In his reconnaissance visits to El Abajo (The Blue), El Late (The Ute), and La Plata Mountains, the writer made collections in addition to field-studies. A comparison of these specimens with the diorite porphyries of La Sal Mountains demonstrates some differences in structure and mineral composition, but when the points of similarity are considered the differences become insignificant. These petrological studies have simply reaffirmed the evidence of the remarkable consanguinity of the laccolithic magmas of this part of the United States, a fact pointed out by the earliest investigators and continually substantiated by succeeding investigations.

IV. Structural Geology

Structural Features of the Plateau Country

Instead of being flat-lying, as is one's first impression, the sediments of the plateau country about the mountains are found to be gently folded. Particularly noteworthy are the anticlines which now exist principally as anticlinal valleys. The limbs of these structures are generally low and flat-lying, but they are much more perfectly developed than the intermediate synclines. Longitudinal or strike faults are characteristic of the anticlines and in some cases, as in the upper end of Spanish or Moab Valley, block-faulting has also occurred. All these structures have a general northwest to southeast trend.

[21] Gilbert, G. K., *Report on the Geology of the Henry Mountains, U. S. Geog. and Geol. Surv. of Rocky Mt. Region*, 1907, p. 60.

[22] Peale, A. C., *U. S. Geol. and Geog. Surv. of the Territories, 10th. Annual Report for 1875*, 1877, p. 95.

[23] Emery, W. B., *op. cit.*, p. 357.

On the Utah side of La Sal Mountains, Castle Valley, with its continuation of Salt Valley, and Spanish or Moab Valley are the principal anticlinal structures. Across the Colorado line, Sinbad, Paradox and Gypsum valleys may be continuations of similar Utah structures. The Castle and Spanish valley anticlines are of further interest because of the manner in which their alignment coincides with the axes of the doming of the north and south groups of the mountains. As may be noted from the geological map (Map 3), the axis of intrusion of the northern group is decidedly in a northwest to southeast direction, in direct alignment with Castle Valley. From the mountains of the north group it is seen that the limbs of Castle Valley flatten out as the axis approaches the Colorado River, only to reappear on the western side as Salt Valley anticline. The limbs of Castle Valley have a dip of from 4 to 5 degrees, but when the structure reappears on the farther side of Colorado River the dip is practically doubled, with the result that the anticlinal character of Salt Valley is much more pronounced than that of Castle Valley. Its limbs project high above the surrounding plateau country, so that it may easily be seen for many miles from almost any direction.

An interesting detail in the structure of Castle Valley is Porcupine Ridge which lies along the south rim adjacent to the mountain group. This ridge seems to be a portion of the valley wall which has faulted or slid downward.

As one looks eastward from the tops of the mountains of the north group into Colorado, the anticlinal Paradox Valley is a very prominent feature. It seems to be a continuation of the Castle Valley and the north group anticlinal structure. No opportunity was afforded to follow the axis of the Utah structure into Colorado, but from the mountains excellent views of all these structures may be obtained and the relationship suggested above seems a very reasonable one. Though the relationship is not clear as was the case with the north group, the doming of the south group is seen to be in alignment with the axis of Spanish Valley. The probable continuation of this structure into Colorado is not so clear as in the case of the northern group.

All these anticlinal valleys are traversed by conspicuous faults. Prommel,[24] who has studied these structures farther away from the mountains and also the anticlines down the Colorado from Spanish Valley, notes that the vertical displacement of the faults increases toward the mountains and that the structures down the river, which are entirely outside the area of possible effect from the mountain uplift, are practically unaffected by faulting. This suggests that the faulting is intimately associated with the mountain uplift. The vertical displacement along these strike-faults varies from almost nothing to 3,500 feet. A great fault with strike parallel to the axes of the anticlinal valleys passes south of the mountains in the vicinity of the property of the Big Indian Copper Company. Another similar break of undetermined displacement was noted north of the north group.

As regards minor structures the sediments of the plateau country are in many cases conspicuously jointed. As already pointed out, these structures have had a very marked effect on the weathering and erosional processes. The Wingate (Pl. V, Fig. 2) and the Navajo exhibit especially well developed vertical joints. These two formations constitute the principal cover rocks north and west of the mountains, so that weathering and erosion have caused the joint systems to become more noticeable than in other formations.

Structure of the Mountains

Though La Sal Mountains have always been considered laccolithic in origin, they exhibit many structures which depart widely from those which true laccoliths should have. The north group, except for Mt. Haystack, and the south group, may be considered as true laccolites. It is within the central group that the different structural conditions are developed.

In neither the northern nor the southern group is the floor of the igneous core of the mountains exposed. The horizon of intrusion is inferred to be immediately below that represented by the stratification contacts found around both these groups. The ridge southeast of Beaver Basin, Red Mountain, Burro Pass and

[24] Prommel, H. W. C., *op. cit.*, p. 393.

the ridge just back of the Warner Ranger station all show actual contacts. The contact rock is found to be a series of grey to maroon arkoses, grits, conglomerates, sandstones, shales and some limestones. Lithologically the beds seem to be equivalent to the Cutler as studied in Castle Valley and elsewhere about the mountains. Furthermore, Little Round Mountain is probably the product of the same period of igneous activity as that which caused the formations of the mountains proper, and though its floor is not exposed, beds of undoubted Permian age are exposed at a distance from it and are seen to dip away as though it had been involved in its formation. In the discussion of the sedimentary rocks associated with the mountain region, it was pointed out that the Cutler beds resemble the Rico lithologically to so marked a degree that it is often difficult to delimit the two formations. And though no beds of known Rico age were found about any of the contact zones, it is not advisable to assume definitely that the Rico has not been involved in the formation of the mountains. On the basis of the thickness of the exposed shaly contact zone it is believed that the igneous mass is either intraformational, i.e. in the lower part of the Cutler, or interformational, i.e. between the Cutler and the Rico. Overlying this shaly horizon of intrusion come the thinly bedded rocks of the Shinarump and the Chinle, above which are the massive competent Wingate and Navajo sandstones.

Grits, conglomerates, sandstones and shales similar to those exposed about the north group are found at the contact zones southwest of Mt. Tukunikivats of the south group, from which it is inferred that the horizon of intrusion is here the same as in the north group.

In both the end groups with the upturned sediments about them, the shaly zone in contact with the igneous core has eroded much more rapidly than the competent Wingate and Navajo sandstones farther removed. Pronounced hogbacks have therefore been developed in many places (Pl. VIII, Fig. 2).

In all the contact areas about both the north and the south groups the upturned sediments were found to be dipping steeply. In no place was a dip of less than 45 degrees noted and along the

western side of the north group the sediments are in some places practically vertical (Pl. VIII, Fig. 1). The intrusion into this group was essentially unsymmetrical with the steeper side along the western flank. In the south group the intrusion seems to have been more nearly symmetrical and in no case were the sediments found to be dipping so steeply as along the western flank of the north group. The change in dip from the steeply dipping conditions about the mountains to the nearly flat-lying position of the strata in the adjacent plateau country is very abrupt, especially along the western side of the north group. Immediately north of the north group just above the village of Castleton, the dip of the sediments, instead of flattening out into the characteristic mesa-like structures found elsewhere, reverses, with the formation of a rather sharp syncline.

Though the contacts around the north group are characteristically stratification contacts, it will be noted that along the northern border of the intrusion the rising magma broke across the strata in several places instead of doming them upward. This part of the mountain mass is also intersected by a number of short dikes, one of which at least, as already noted, not only cuts the porphyry mass but extends outward into the upturned sediments that constitute Red Mountain.

Mention has already been made of Little Round Mountain and though it does not come within the area covered by the map, it is no doubt an intimate associate of the mountain group proper, and at greater depth might show a more intimate relationship with the igneous core of the north group than now appears to be the case. So far as they can be observed, the structural features associated with this igneous butte are identical with those that characterize the north group proper.

As already noted, Mt. Haystack, though apparently a part of the north group, is yet quite different structurally from the remainder of the intrusion. An immense amount of slide rock has covered the contacts on every side except for a few feet of McElmo and Dakota beds which are exposed along the south side. These are not sufficient to give a definite clue as to the exact structure of the mountain. It appears to have been an

intrusion which was so rapid that it cut across the sedimentary rocks instead of doming them up, except for small portions of the upper formations, i.e., the McElmo and the Dakota, which were locally so sharply upturned by the intrusion that the only outcrops visible have a vertical dip. Mt. Haystack seems therefore to be essentially a stock (Fig. 2).

In the south group what appears to be a finger from the main intrusive mass underlies Moore's Ridge (Fig. 3). The anticlinal character of this ridge is very evident, with the rocks dipping away on either side. The crest of the ridge is covered with the Navajo sandstone which is separated into great blocks and which seem to have resulted from tensional stresses brought about by the force of the upwelling magma below.

It is in the central group that the conditions of intrusion seem to have been particularly complex. Wherever they are exposed about this group the sediments are found to dip toward the igneous core at an angle of about 5 degrees. When these dipping beds are followed toward the intrusive center, it is found that the exposed porphyry masses are above the level of most of these dipping sediments, that is, the exposed igneous masses do not seem to have caused the slight doming of these sediments. The suggestion at once arises that the exposed portion of the intrusion represents but a part of the main intrusive mass and that at greater depth below the gently domed strata exists another horizon of intrusion. A study of individual mountains substantiates this view; a particularly interesting example is Mt. Mellenthin.[25] From the Horse Canyon side the entire floor of this mountain is clearly exposed and the horizon of intrusion is seen to be at the base of the Mancos shale, just above the Dakota Sandstone. Considerable quantities of the Mancos shale are included in the porphyry mass at different levels. The feeders which supplied the magma to form this mountain are represented by a number of dikes which are clearly exposed along the east wall of Horse Canyon. These dikes cut upward from some unexposed source through the McElmo and the Dakota

[25] Gould, L. M., "A 'Laccolite in the Air,'" *Papers of the Michigan Academy of Science, Arts and Letters*, 5: 253–256.

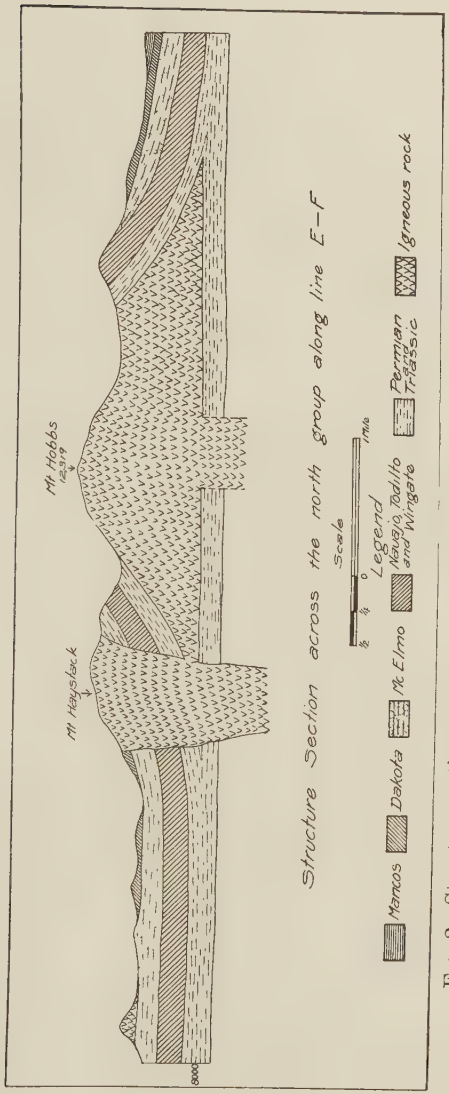


FIG. 2. Structure section across the north group along the line E–F of the geologic map

into the Mancos where the magma spread laterally. The thickest portion of the possible buried mass beneath the mountains of this group appears to be south of Mellenthin in the direction of Mt. Peale, for it will be noted from the structure section (Fig. 4) that the floor of Mt. Mellenthin is dipping upward in the

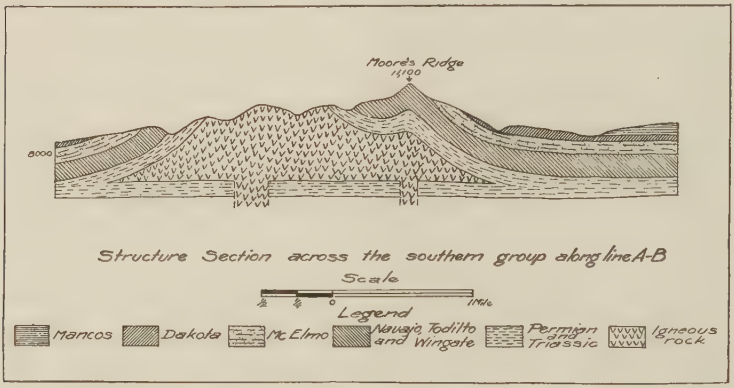


FIG. 3. Structure section across the south group along the line A–B of the geologic map

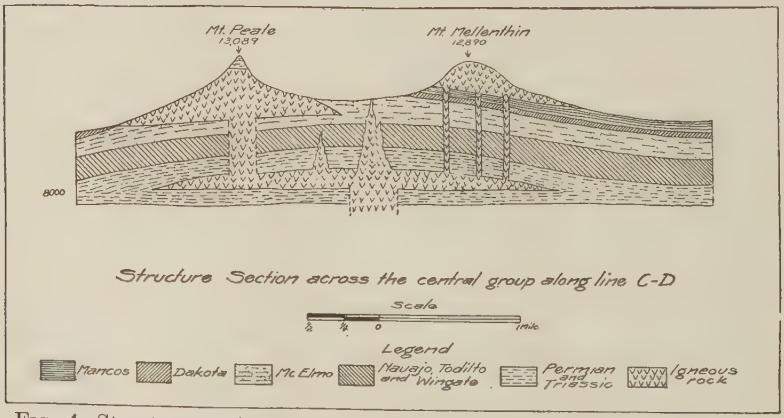


FIG. 4. Structure section across the central group along the line C–D of the geologic map

direction of Mt. Peale. The latter mountain is the highest in the entire La Sal area and unlike any other peak it is capped by flat-lying sediments. These sediments are somewhat metamorphosed and discolored, but are believed to be from the lower portion of the McElmo. They do not, apparently, represent part of a fold that once covered the mountain, but they seem rather to have been broken off and carried upward by the immense force of a rising magma from below. A small exposure of practically flat-lying sediments is found on the southwest flank of this mountain. This may be the formation from which the strata on the top of Mt. Peale were broken off. Furthermore stratification contacts are notably lacking about Mt. Peale. In only one place and there for but a few feet were any sediments dipping away from the igneous mass with such contacts. Rather the beds involved in the intrusion are but slightly tipped up, the magma for the most part having broken across them.

The third principal peak of the central group, Mt. Allen, presents still more complex structural conditions than either of the other two. On the south and west sides the McElmo beds are slightly upturned about the porphyry core, but not to such an extent as to form stratification contacts. On the south side, where erosion has cut deeply into the mountain, a wedge-shaped dike cuts upward into the sediments and sends out small lateral sheets into the shaly beds of the McElmo. On the Gold Basin side of the mountain this sort of structural feature is more pronounced. Toward the head of this basin, where one may see a considerable vertical section through the structure, sheets are seen to spread out into the McElmo beds from Mt. Allen and from dikes which cut upward through the masses of sediments and interstratified sheets. Though the McElmo beds seem to be the principal ones in immediate contact with the porphyry mass of Mt. Allen and the strata into which the rising magma mainly intruded itself as sheets, beds much lower stratigraphically seem to have been disturbed in the formation of this mountain, that is, it does not seem to be the product of a magma which rose through one or through a number of conduits and which upon reaching the McElmo in part insinuated itself into this

formation and in part domed it up. On the western flank of Mt. Allen considerable portions of a maroon conglomerate with boulders as much as eight inches in diameter were found. I know of no formation in this general region from which such a rock might have come except the Cutler. It seems, therefore, that Mt. Allen is the result of an intrusion of stock-like character, which probably does not possess associated magma sheets except within the McElmo. Its rise through the beds above the Cutler, until it reached the McElmo, was so rapid as to cut completely across them except for the small area noted on the west flank.

The isolated patches of igneous rock which lie to the west and northwest are probably parts of the same intrusion as that which constitutes Mt. Allen. Further erosion will very likely reveal a more intimate relationship at greater depth.

It has been pointed out that the porphyry mass capping the lower end of the ridge north of Gold Basin is a flow. Its floor is plainly seen to be the McElmo beds which are entirely undisturbed about it. A pronounced fluxion structure also characterizes this rock.

The small igneous mass at the upper end of this ridge was probably formed contemporaneously with Mt. Mellenthin, for it is in the same horizon. The formation of Horse Canyon has separated it from the major part of the intrusion. The ridge that extends northeast of Mt. Mellenthin is seen to be composed principally of igneous rock. This mass seems, however, to have no intimate relationship with Mt. Mellenthin, for it has disturbed the McElmo beds about it; that is, its horizon of intrusion is below the base of Mt. Mellenthin.

The dikes which are associated with this group of the mountains are in part radial, as is seen, from visible igneous masses (see Map 3). In part they seem to be roof dikes to some unexposed mass below. Particularly interesting in this connection is the dike which strikes northwest-southeast along the upper north side of Gold Basin. It appears to be a wedge-shaped dike thinning rapidly toward the top. Its exposure does not at any place studied exceed thirty feet in width. Some years ago a

mining company drove a tunnel into and near the bottom of the north wall of Gold Basin approximately at right angles to the probable continuation of this dike. In the summer of 1921 it was still possible to go into this tunnel, which penetrates nearly a hundred feet into the porphyry mass with the end of the tunnel still in the igneous rock. This igneous body appears to be the lower portion of the narrow dike outcrop several hundred feet higher up the side of the basin.

From a general view of the structure of this entire group it seems that, just as was the case in the end groups, there was an intrusion in or below the Cutler beds, but for reasons which will be given later the intrusion did not here greatly dome up the overlying strata. Instead, the magma broke through the roof of this lower horizon so as to well upward through the smaller fissures and form dikes. Through others it formed conduits or feeders, intruding itself at different horizons according to local conditions of structure, viscosity of the magma, or as the rate of intrusion may have controlled. Mt. Allen seems to have been a breaking upward from a small portion of the lower intrusion itself. In the case of Mt. Peale the magma welled upward until it reached the lower part of the McElmo, where it spread out and continued to rise with such great force as to break off and carry upward the flat-lying sediments now found upon its top. In the formation of Mt. Mellenthin the rising magma did not spread laterally until it had reached the Mancos shale. The three main mountain masses of this group illustrate gradational phases between true laccoliths and stock-like structures. Mt. Allen suggests a stock; Mt. Peale represents a more intermediate stage, an imperfect sort of laccolith, while Mt. Mellenthin appears to be a true laccolith. As already noted the porphyry of this mountain is intruded into the Mancos shale. To judge from the attitude of a few outcrops of this shale to the north of the mountain, it seems to have covered the igneous core and formerly it may also have had small intruded sheets of porphyry, which have since been eroded.

V. The Origin of La Sal Mountains

REVIEW OF THEORIES ON THE ORIGIN OF LACCOLITHS

Powell [26] seems to have been the first investigator to make any suggestion concerning the possible origin of the laccolithic mountains of the southwestern part of the United States. He thought the Henry Mountains, which he named, were formed by quantities of molten matter pouring out through fissures and spreading over the country before it had been eroded to its present depth. Later investigators of the Hayden Survey pointed out the error of Powell's suggestion and demonstrated the intrusive character of these mountains. Peale [27] in 1877 assembled the information available concerning these so-called "eruptive" mountains of the southwest. He concluded that they were all the result of igneous material which came up through fissures in the sedimentary rocks, in some places only slightly tipping up the ends of the strata, and which upon reaching the Cretaceous shales generally spread out in them.

It was Gilbert [28] however who first gave a statement of the more exact character and probable cause of this type of mountain. His idea is so concisely stated that it merits quoting in his own words. After pointing out that it is usual for igneous rock to ascend to the surface of the earth and there issue forth to form mountains or hills, he adds: "The lava of the Henry Mountains behaved differently. Instead of rising through all the beds of the earth's crust, it stopped at a lower horizon, insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap. For this body the name *laccolite* (from two Greek words meaning cistern and stone) will be used."

[26] Powell, J. W., *Exploration of the Colorado River of the West and Its Tributaries, 1869-1872*, pp. 177–178. Smithsonian Institution.

[27] Peale, A. C., *On a Peculiar Type of Eruptive Mountain in Colorado. U. S. Geol. and Geog. Surv. of the Terr.*, Bull. No. 3, III: 550–564.

[28] Gilbert, G. K., *Report on the Geology of the Henry Mountains, U. S. Geol. and Geog. Surv. of the Rocky Mt. Region*, 1877, p. 19.

In 1893 Cross [29] published a very comprehensive account of the geology of the laccolithic areas of the southwestern part of the United States, in which he suggested a new force operative in the formation of this type of mountain. Gilbert ascribed the entire doming of the strata to the hydrostatic force of the rising magma, but Cross believes that orogenic stresses are necessary, in a few cases at least, to account for the doming of the sediments over some of the laccoliths which he describes. He does not appear ready, however, to go so far as Steinmann [30] in the matter of the relationship between folding and igneous intrusion. The latter, in discussing the relationship between the Andes and their igneous core, expressed the belief that the space for the intrusive mass was formed by the folding itself. Hobbs [31] would carry over to laccolithic mountains the ideas expressed by Steinmann with reference to Andean structure; that is, he ascribes to regional compressional stresses the entire cause of the doming of the strata over laccolithic mountains. He believes further that the laccolithic magmas themselves are not the products of intrusion in the ordinary sense, but rather that they have resulted from the fusion of shales upon the pressure being relieved by the doming of the competent structures above. McCarthy [32] has recently given an excellent review of the various notions concerning laccoliths and has further pointed out the importance of such factors as the rate of intrusion, and the viscosity of the magma, as well as of orogenic stresses in the effects that all these may have had upon the structures resulting from intrusions. His conclusions are based further upon experimental data which in part seem to have excellent representatives in some La Sal Mountain structures, as will be pointed out later.

[29] Cross, Whitman, "The Laccolithic Mountain Groups of Colorado, Utah, and Arizona," *Fourteenth Ann. Rept. Direction, U. S. Geol. Survey*, Part II, 1893, pp. 165–238.

[30] Steinmann, G., "Gebirgsbildung und Massengesteine in der Kordillere Südamerikas," *Geol. Rundsch.*, 1 (1910): 13–35.

[31] Hobbs, W. H., *Earth Evolution and Its Facial Expression*, pp. 53–58.

[32] McCarthy, G. R., "Some Facts and Theories concerning Laccoliths," *Journ. of Geol.*, XXXIII (1925): 1–18.

APPLICATION OF THESE THEORIES TO LA SAL MOUNTAINS

The structural conditions of the central group of La Sal Mountains are so different from those of the end groups that one is forced at the outset to the conclusion that greatly differing conditions of formation obtained in the various groups. In other words, no one of these theories, without some modifications, explains all La Sal Mountain structures.

The Central Group

It has been pointed out that the north and south groups show a definite alignment with anticlinal structures of the plateau region. Here the relationship of orogenic stresses to the formation of the mountains is evidently a very intimate one. In the central group there is no evidence that such stresses played any part. The plateau areas adjacent to this group are flat-lying or even slightly synclinal, since they represent the region between the well-developed Castle Valley and Spanish Valley anticlines. The structures of this group seem to be explained by Gilbert's theory in which the hydrostatic force of the ascending magma was the sole cause of the rupturing and upturning of the sediments. McCarthy's experiments, as described in the paper referred to, suggest that the rate of intrusions has a great effect upon the character of structures. Other things being equal, if the intrusion be sufficiently slow the round-arch type of laccolith represented by the Henry Mountain is formed. At the other extreme with too rapid rate of intrusion stocks result. In the central group of La Sal Mountains, except for the postulated lower horizon of intrusion which, if present, is a thickened sheet or a greatly thinned laccolith, the structures indicate that the rate of intrusion was too rapid to allow a complete doming of the overlying strata with the development of stratification contacts, after the fashion of the Henry Mountains. Mt. Mellenthin may be an exception to this statement, for though the strata above its horizon of intrusion are almost entirely eroded, the remnants suggest that it represents the Henry Mountain type of structure. As regards the other mountain masses of this

group, the ascending magma rose with such force that it cut across the sediments in some places, insinuated itself between the strata in others, and in still others tipped up the surrounding sediments, but rarely with the formation of stratification contacts. These mountains really represent intermediate stages between true laccoliths and stocks.

The North and South Groups

So far as the end groups of the mountains are concerned, Gilbert's theory of the doming of the strata as due solely to the force of an ascending magma, is clearly inadequate. It is hardly conceivable that the intrusion of so great a mass as that represented by either of these end groups could take place uninfluenced by outside factors, especially with the formation of sediments so steeply upturned about the igneous cores, without the formation of numerous radial dikes. When one considers the great differences between the structures of the central group as compared with the north and south groups, it is at once apparent that the anticlinal structures of the plateau country associated with these two groups truly indicate that orogenic stresses have played a very important part in the doming of the strata over the igneous cores. It is, therefore, apparent that the structural features of the end groups accommodate themselves more nearly to the theory of the fusion of shales or to the idea that orogenic stresses even to the point of folding accompanied or preceded the intrusion of the magma. It should not be inferred from this statement that the writer believes that folding must proceed to such a point as completely to form reservoirs in order that such structures as those represented by the end groups of La Sals may form. Indeed the hydrostatic force of a rising magma may have been the major force, with the orogenic stresses in the nature of incipient folding simply acting as a rudder.

Quite like the other laccolithic mountains of the southwestern United States, extensive contact metamorphic effects are notably lacking in all three groups of La Sal Mountains. There have been bleaching and discoloration of the red rocks of the contact zones in the north and south groups and in a few

places, notably Red Mountain of the north group, some shales have been changed to slate and small amounts of iron ores have been developed. But these contact effects are much less pronounced than one might expect to be produced by the intrusion of so great a mass as that represented by the north group especially. It has been customary for investigators to explain this general absence of great contact metamorphic effects about laccoliths on the basis of the temperature of the intruding magma; the supposition has been that magmas might be intruded at so low temperatures and with so small an amount of mineralizers that no appreciable contact metamorphic effects were produced. Hobbs takes a different view and attaches great importance to the absence of such effects in support of his theory of the fusion of shales.

The inference from this theory is that the temperature of a magma formed in such a manner would so closely approximate that of the country rock that the tendency for contact metamorphic effects would be reduced to a minimum.

Cross [33] has shown that the geologic horizons occupied by laccoliths range in age from the Cambrian to post-Laramie. So far as they are expressed by the structure, the conditions of cooling in the highest were identical with those in the lowest. The conclusion is inevitable, therefore, that several thousand feet of sediments must have covered the highest of these laccoliths at the time of their formation. In view of the depth below the surface necessited by so great a load, the temperatures at the horizons of intrusion of the various laccoliths may well have been so high that magmas could easily have been intruded at temperatures approximating those of the country rock. Furthermore, if the igneous masses which now constitute the cores of laccoliths were formed by the fusion of adjacent bodies of shales, some evidences of such fusion ought to be preserved. Gradational phases between the shales and their igneous equivalents should be found especially about the contacts and in connection with the masses of shales included in the porphyry bodies. Cross [34] notes that the statements of Peale and Holmes that the magmas

[33] Cross, Whitman, *op. cit.*, p. 239. [34] *Ibid.*, p. 230.

"absorbed" sedimentary masses are not supported by definite evidence of fusion. Neither in such masses of shales as those found included in the porphyry body of Mt. Mellenthin, nor about any of the contacts in La Sal Mountains is there any evidence of such fusion. The contacts between the two kinds of rock are sharp and furnish easy planes of parting. El Abajo and El Late Mountains are intruded into Cretaceous shales. None of the contacts studied about either of these groups showed any evidence of assimilation of the shales by the igneous mass. In La Plata Mountains brief studies were made of Mt. Hesperus and Banded Mountain with their remarkable banding due to the interbedded shales and sheets of porphyry. Though some slight metamorphic effects are noticeable, the lines of demarcation between the shales and the igneous rock are generally well defined and give no suggestion of an intimate genetic relationship.

CONCLUSIONS

In trying to arrive at a proper conclusion with reference to the origin of La Sal Mountains, I have dealt with the various groups as though they might not be intimately associated. Such is not the case. Indeed the igneous cores of the three groups, at the horizon of intrusion of the north and south groups, may be connected beneath the sedimentary saddles. There is no evidence that the entire mountain uplift is not the result of a single or of a number of closely spaced periods of igneous activity. Viewed as a whole then, La Sal Mountains seem to be unusually well developed examples illustrating the profound effects that orogenic stresses may have upon the structures produced by laccolithic intrusions. The differences in the structure of the end groups as compared with the central group may be entirely accounted for by the fact that in the central group the intrusion was uninfluenced by folding stresses, hence the complex structures and semi-stock-like character of parts of this group. In the end groups horizontal compression to the extent of folding affected the intrusions in such a manner as to allow the doming of the surrounding strata without the development of widespread tensional effects.

THE AGE OF LA SAL MOUNTAINS

The youngest rocks exposed anywhere near the mountains are the Mancos shales of Cretaceous age. These have been involved in the mountain uplift. Therefore beyond the statement that the intrusion was at least post-Cretaceous, nothing definite can be said about the age in which the Sierra La Sal were formed. Cross [35] has pointed out that the West Elk Mountains in Colorado are certainly Tertiary in age and that everything suggests that the other groups, including La Sal Mountains, are of the same age.

The field-work upon which this report is based was conducted during the summers of 1921 and 1924, which were spent in La Sal Mountains and in neighboring regions. This extensive work was made possible only because of the very generous financial assistance of Mr. R. C. Allen of Cleveland, in whose honor Mt. Allen is named.

University of Michigan

[35] Cross, Whitman, *op. cit.*, p. 238.

PLATE I

Fig. 1. Castle Butte in Castle Valley

Fig. 2. Arches in the Upper Navajo Sandstone

PLATE II

Fig. 1. Mt. Hobbs at the Head of Beaver Basin, showing Schrund Line

Fig. 2. Typical Forms of the Navajo on the "Sand Flats," Where It Is the Cover Rock

PLATE III

Fig. 1. Cirques at the Head of Deep Creek Basin

Fig. 2. Gold Basin showing U-shaped Valley and Cirque

PLATE IV

Fig. 1. Pratt's Lake in Dark Canyon, a Morainal-dam Lake

Fig. 2. Rock Glacier in Lower Part of Deep Creek Basin

PLATE V

FIG. 1. Unconformity between Permian and Triassic exposed in Colorado Canyon

FIG. 2. Mesa in Lower End of Castle Valley
The lowest rock exposed is Cutler and the cap rock is the Wingate

PLATE VI

The Canyon of Mill Creek near the Central Group

A is the Lower Navajo; *B*, the Middle Navajo; *C*, the Upper Navajo; *D*, the McElmo

PLATE VII

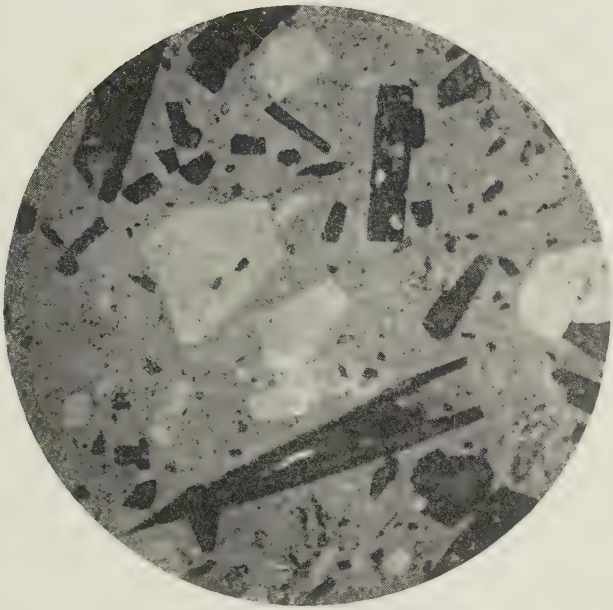


Fig. 1. Photomicrograph of Diorite Porphyry showing Acicular Development of the Hornblende

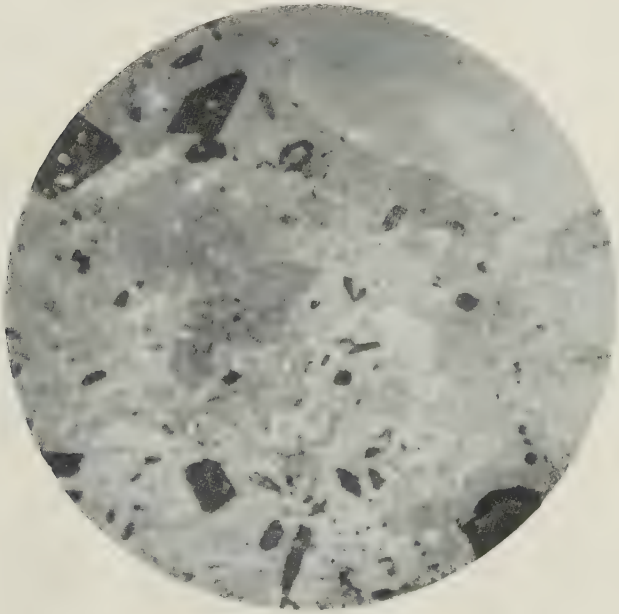


Fig. 2. Photomicrograph of Diorite Porphyry showing Characteristically Twinned Crystal of Augite

PLATE VIII

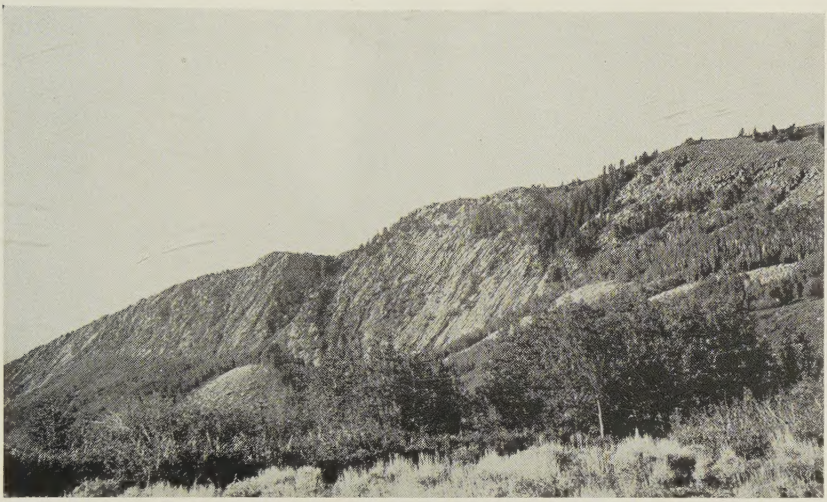


Fig. 1. Hogback of Dakota Sandstone along the Western Side of the North Group

Fig. 2. Hogback of Massive Triassic Sandstone along the Southern Side of the North Group